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MAIN DIRECTIONS OF PROGRESS IN SOLID STATE MICROWAVE ELECTRONIC--ETC(U)

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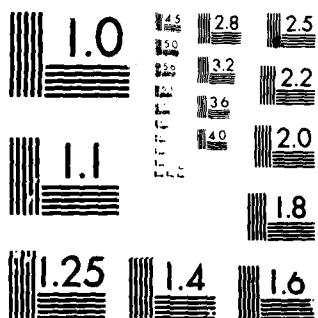
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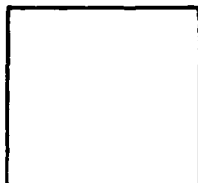


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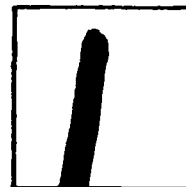
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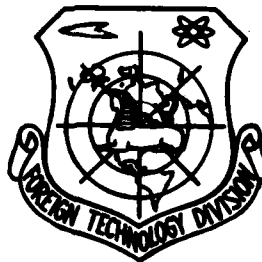
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MAIN DIRECTIONS OF PROGRESS IN SOLID STATE MICROWAVE ELECTRONICS

by

Adam Smolinski



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PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
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MAIN DIRECTIONS OF PROGRESS IN SOLID STATE MICROWAVE ELECTRONICS*

Adam Smolinski

It has become a tradition for national conferences on Solid State Microwave Electronics (SSME) to start by discussing the main directions of progress in this field during the preceding three years.

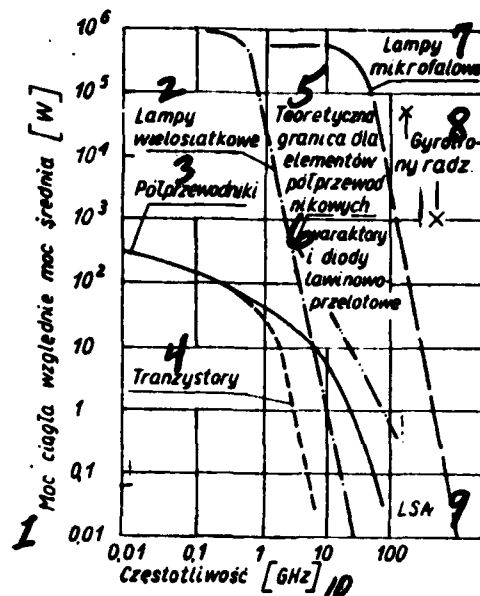
I should like to refer here to a statement made three years ago that SSME has already reached a certain technical maturity and that many technological, construction and measurement problems have been mastered, leading to the production of microwave elements and solid state integrated systems which not only operate under terrestrial conditions but also function in cosmic space. One could even go so far as to state that the SSME elements have made possible the present advances in satellite communications. It is necessary, however, to note that this maturity we claim applies mainly to waves in the decimeter and centimeter range. Transition to shorter waves, down to sub-millimeter range, will still require extensive research and, particularly, industrial effort. It is well known that these waves can send a larger amount of information and at a higher accuracy.

In addition to the progress in the "frequency" area, there is an effort to increase the range of operation of the installations with higher power and less noise. The power reached by semiconductor elements was already much closer to the theoretical limit of the utilization of material (Fig. 1). However, we approach kilowatts of mean power only with the greatest difficulty and effort. We shall discuss specific advances in this area later on; here I should like to mention

* A summary of inaugural address at the IV National Conference on Solid State Microwave Electronics, Gdansk, October 17, 1977.

Fig. 1. Mean power provided by generators of various types in microwave range.

1 - Continuous power or mean power [W]; 2 - multigrid lamps; 3 - semiconductors; 4 - transistors; 5 - theoretical limit for semiconductor elements; 6 - variators and cascade-transit diodes; 7 - microwave lamps; 8 - Soviet gyratrons; 9 - LSA; 10 - frequency (GHz)



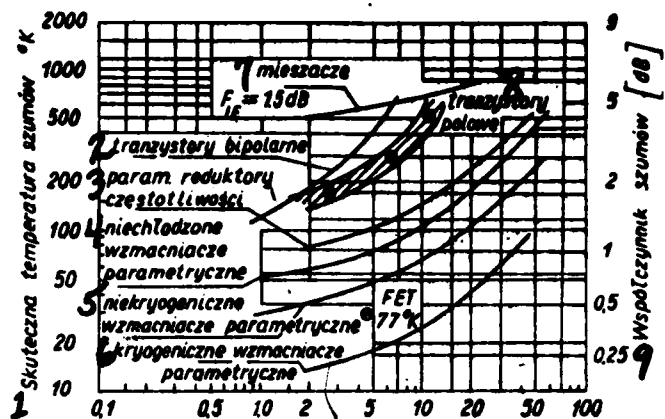
only the development of gyratrons. These are lamp generators combining the advantages of masers and klystrons. They utilize strongly relativistic beams of electrons to create oscillations at the centimeter and shorter waves range, down to parts of a millimeter, and produce a mean power of several tens to several hundreds of kilowatts at millimeter waves [1, 2]. This achievement may find applications in radar and plasma installations [3].

Such a great power, reaching a gigawatt in impulse, can be provided by a cloud of monoenergetic electrons in a waveguide excited with crossed permanent fields -- electric and magnetic. Electrons moving in a spiral and retarded by a screen lose energy to the signal wave in the waveguide at a frequency higher than the cyclotron frequency. Gyratrons produce radiation at a wave determined by the magnetic field and not by dimensions of resonance structure. This fact allows the achievement of very high powers at relatively low energy densities.

The other line of progress in the microwave field is seen in low-noise elements at millimeter waves. One has to mention

Fig. 2. Effective noise temperature of various semiconductor systems as a function of frequency.

1 - Effective noise temperature, °K; 2 - bipolar transistors; 3 - parametric reducers of frequency; 4 - non-cooled parametric amplifiers; 5 - non-cryogenic parametric amplifiers; 6 - cryogenic parametric amplifiers; 7 - mixers; 8 - field effect transistors; 9 - noise coefficient (dB).

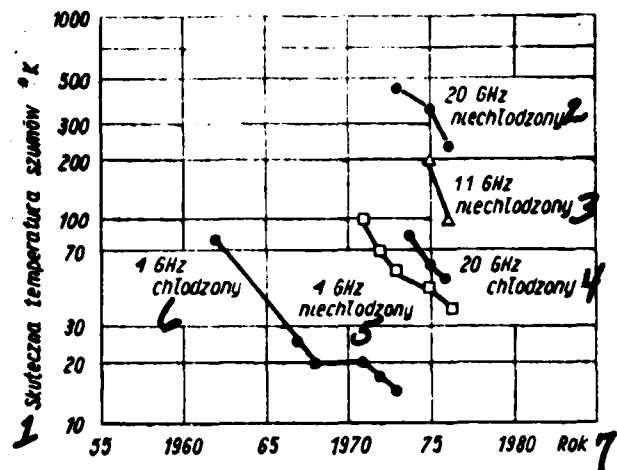


here a new development, a semiconductor-superconductor diode, called the super-Schottky. When working as a heterodyne detector at the temperature of liquid helium, it has an effective noise temperature of 6° K at 9 GHz (Fig. 2) [4]. On the other hand, one can note another record at millimeter waves (200 - 325 GHz), namely, the effective temperature 1320° K (co-responding to the noise coefficient 7.4 dB), also of cryogenic mixer with losses 6.5 dB and bandwidth $B = 20$ MHz, working with the Josephson junction and 9 GHz maser amplifier of intermediate frequency [5]. Systems of this type find application in radio astronomy, in investigation of the properties of the atmosphere and plasma, and lately in aerial radiometers.

Both of these mentioned achievements already exceed the limits of the well-known graph of the effective temperature of noise versus frequency for various semiconductor systems. This graph shows quantitatively the progress in a number of applied systems. One has to note the data on the cryogenic parametric amplifier, which now replaces the earlier used maser. Figure 3 shows the lowering of noise of parametric amplifiers, cooled and non-cooled, which took place in recent years. This process was the result of advances in the fields of the technology of materials and instruments.

Fig. 3. Effective noise temperature of parametric amplifiers.

1 - Effective noise temperature, °K; 2, 3, 5 - non-cooled; 4, 6 - cooled; 7 year



This progress manifests itself clearly in field effect transistors of gallium arsenide, which by now have become very reliable elements produced on a factory scale and are finding application in varied cases [6]. The original basic application of these transistors was low-noise amplification. Transistors with the gate of $0.5 \mu\text{m}$ or even $0.25 \mu\text{m}$ are beginning to find general use. In laboratories, the gates of even $0.15 \mu\text{m}$ are produced, which allows broadening of the range of wideband operation above 20 GHz (for instance, up to 26 GHz at 6.6 dB noise coefficient and 5.6 dB amplification). The basic properties of manufactured transistors are illustrated in Fig. 4. The record values of noise coefficients are now from 1 dB for 3 GHz to 5.6 dB for 24 GHz.

On the basis of these facts, a number of amplifiers, in the form of hybrid integrated systems, have been developed for the most frequently used bands. Their noise coefficients are shown in Fig. 5. The construction of amplifiers has been made easier by the development of machine methods of analysis, synthesis and optimization especially for this purpose [7]. The application of cooling with liquid nitrogen (77°K) makes possible the reduction of further noises of the field effect (FET) transistor GaAs, since the thermal noises are predominant [8]. The measured values of the

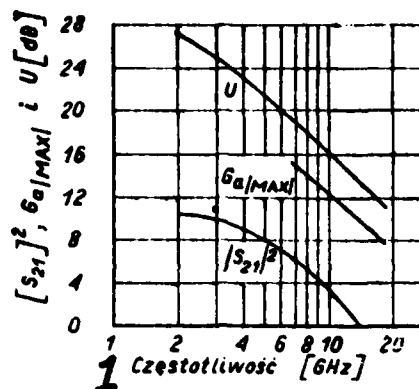


Fig. 4. Unilateral amplification, maximal amplification and $|S_{21}|^2$ of a typical field effect transistor from gallium arsenide with $1 \mu m$ gate.

1 - Frequency (GHz).

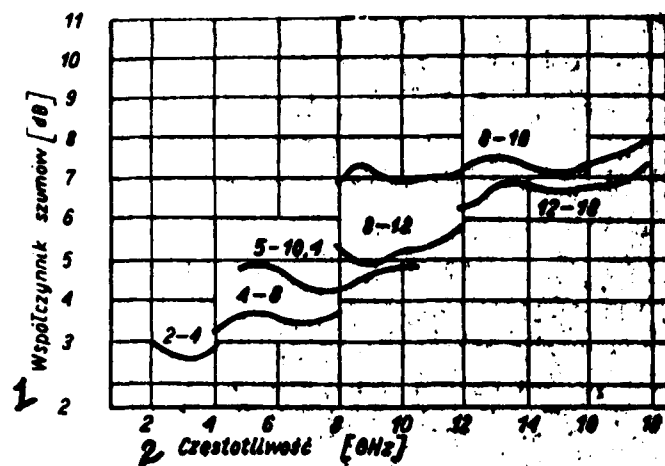


Fig. 5. Noise coefficient of typical amplifiers with field effect transistors from gallium arsenide.

1 - Noise coefficient (dB);
2 - Frequency (GHz).

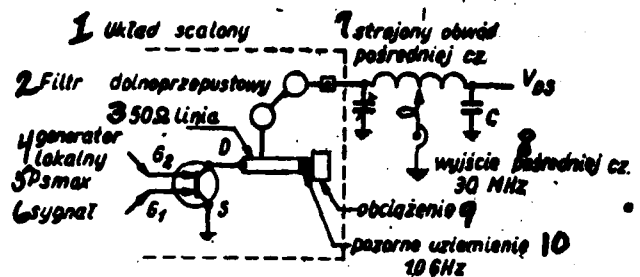
effective noise temperature in the band 4 GHz are now only $30^\circ K$ [9]. This point is also plotted in Fig. 2.

I mentioned previously that field effect transistors of gallium arsenide are finding varied applications. These include recent tests of their use in microwave mixers which, in addition to normal amplification, show a better linearity than the usual diode mixers. Some of them are equipped with double gate, which simultaneously permits both a large amplification of transfer ($G = 11$ dB) and a low level of noise ($F_2 = 6.5$ dB) in the X-band [10]. The schematic of connections of such a mixer is given in Fig. 6. It has to be added here that construction of mixers of this type is now based mainly on experimentation, since there are still no accurate values available for the parameter S for field effect transistors (FET) excited with local oscillators.

Lately the field effect transistors of gallium arsenide have also found application as microwave limiters, utilizing the convenient form of current-potential characteristics for limiting the amplitude of signal [11].

Fig. 6. Microwave mixer with two-gate field effect transistors from gallium arsenide.

1 - integrated system; 2 - low-pass filter; 3 - line; 4 - local generator; 5 - $p_{s \max}$; 6 - signal; 7 - attuned circuit of intermediate frequency; 8 - output of intermediate frequency; 9 - load; 10 - apparent grounding.



These transistors owe their success mainly to their application in low-signal low-noise amplifiers. It has been found, however, that they are perfectly suitable as amplifiers of power at very small deformations. A number of special transistor constructions, containing a series of parallel systems source-gate-drain in one frame, have been developed. The frequency characteristics of various types of such transistors are shown in Fig. 7 [12]. It is seen that their output power already exceeds 1 W at 8 GHz.

The catalogs of various companies give technical data for such transistors. It has to be noted that no values for large-signal parameters S are available, although values for large-signal input and output impedances are included.

When listing the advantages and applications of field effect transistors of gallium arsenide, one should not forget their generating capabilities. We already know that they cause oscillations even at 100 GHz [13], but their main generating applications lie in the centimeter wave range. Based on experimental data in the construction of such generators, because of the mentioned lack of data on the large-signal parameter S , one already gets a part of a watt at 25% efficiency. A more serious shortcoming of the discussed generators is their noise, particularly near the carrier wave, dependent on the quality of gallium arsenide. It is up to 20 dB larger than for the corresponding bipolar transistors of silicon [14]. Intensive work on the development of these generators goes on. It is anticipated that the power of 4 W at 10 GHz will

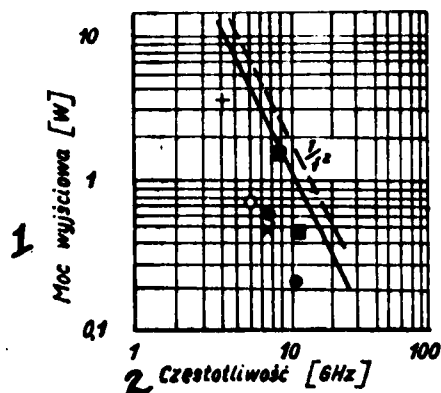


Fig. 7. Increase of output power in field effect transistors from gallium arsenide.

1 - output power (W);
2 - frequency (GHz).

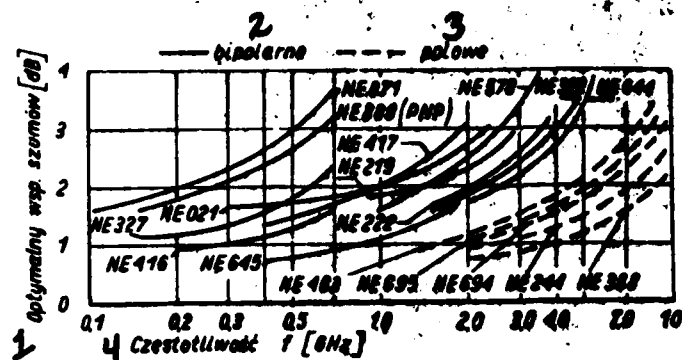


Fig. 8. Noise coefficients of bipolar transistors and field effect transistors.

1 - optimal noise coefficient (dB);
2 - bipolar; 3 - field effect;
4 - frequency (GHz).

achieved in the near future, and at 20 GHz somewhat later on [15]. A high efficiency of generators with the discussed transistors makes them serious competitors with lamps with a running wave. The possibility is considered of applying them in antennas placed on the aircraft.

Here we should finish our discussion on field effect transistors of gallium arsenide. But we have to mention that a new type of field effect transistor made of silicon has appeared on the scene. Silicon is a well-known technologically developed material; therefore, the attempts to utilize it in microwave field should not be surprising. A new field effect transistor of silicon, called SIT (Static Induction Transistor), has a known construction from junction field effect transistors JFET, but in a vertical short channel. Its action consists of injecting the majority carriers into an area emptied of charge, surrounded by the area of gate and controlled by the potential of gate and drain [16]. This transistor is actually a decimeter band transistor, since it generates 100 W at 200 MHz, or provides the output power 13 W in a power amplifier at 1 GHz.

In this general race to modernization, the bipolar transistors are by no means remaining behind. Although they are inferior

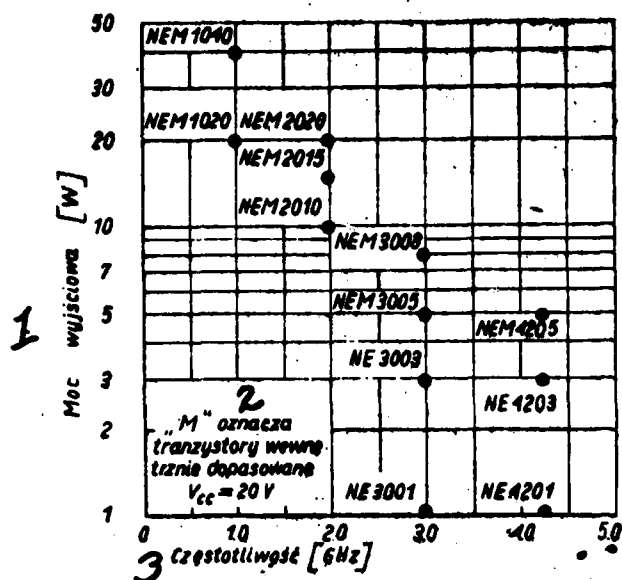


Fig. 9. Output power of bipolar power transistors.

- 1 - output power (W);
 2 - "M" denotes internally matched transistors;
 3 - frequency (GHz).

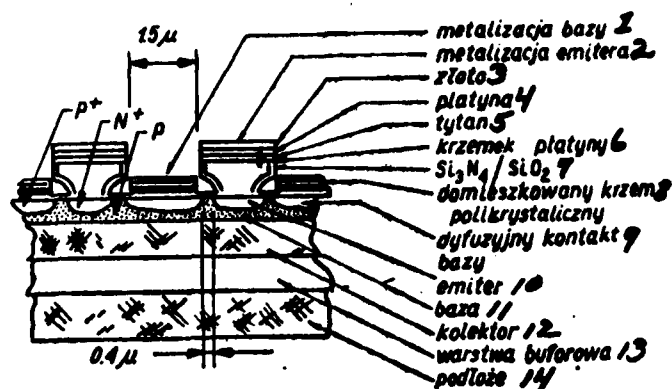


Fig. 10. New construction of bipolar transistor SET (Stepped Electrode Transistor).

- 1 - base metallization; 2 - emitter metallization; 3 - gold; 4 - platinum; 5 - titanium; 6 - platinum silicate; 7 - $\text{Si}_3\text{N}_4/\text{SiO}_2$; 8 - admixed polycrystalline silicon; 9 - diffusional contact of base; 10 - emitter; 11 - base; 12 - collector; 13 - buffer layer; 14 - foundation.

to field effect transistors in their noise in the range of frequency (Fig. 8), they present a serious economic competition in the bands up to 5 - 6 GHz, since their price is lower by at least an order of magnitude. This applies not only to the mentioned low-noise transistors but primarily to power transistors. These transistors reach the power of several watts at the mentioned frequencies, due to the internal matching of output and input circuits. In the range 1 - 2 GHz, special constructions of transistors can provide up to 40 W (Fig. 9). They include, for instance, a new structure called SET (Stepped Electrode Transistor) leading to reduction of the base-collector capacity and base resistance through the introduction of an apparent "zero gap" between the emitter junction and the base metallization (Fig. 10) [17]. One can also obtain even higher powers, for instance 400 W, from a dozen of such transistors connected in parallel [18]. It is expected that the continuous power of kilowatt can be obtained this way within the next few years.

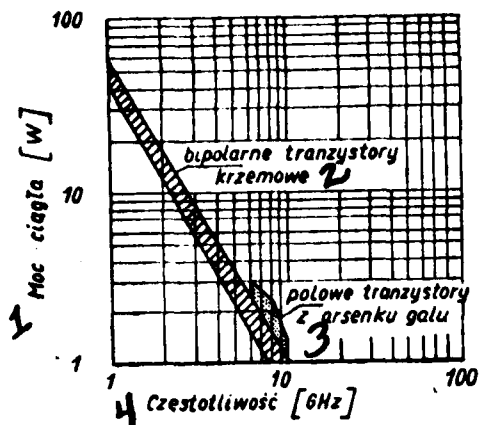


Fig. 11. Comparison of the power of bipolar transistors from silicon with the power of field effect transistors from gallium arsenide.

1 - continuous power; 2 - bipolar transistors from silicon; 3 - field effect transistors from gallium arsenide; 4 - frequency (GHz).

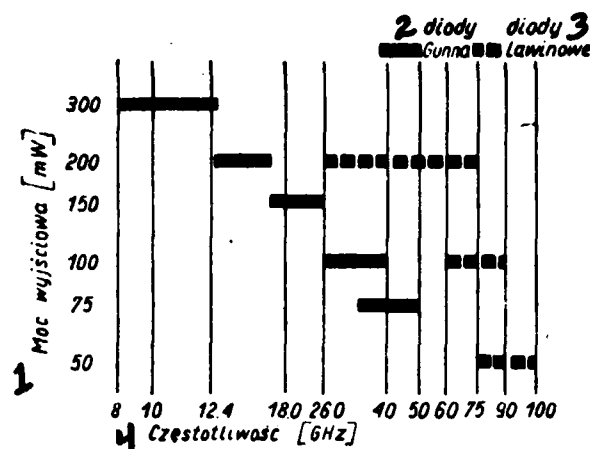


Fig. 12. Comparison of the power of generators with the Gunn diode and with cascade-transit diode.

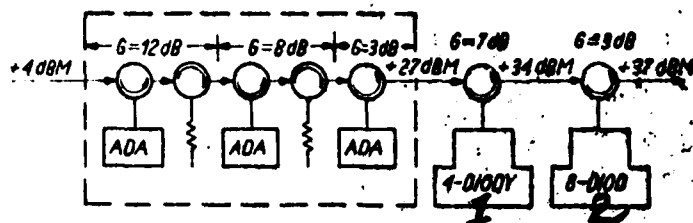
1 - output power (mW); 2 - Gunn diodes; 3 - cascade diodes; 4 - frequency (GHz).

The power obtainable with field effect transistors from gallium arsenide and with bipolar transistors from silicon as a function of frequency is compared in Fig. 11. The data show how far the so-called transistorization of microwaves has progressed. Incidentally, I shall mention yet another bit of pertinent information.

An increase of power in bipolar transistors can be obtained by introducing between the base and collector two additional layers of coatings -- the avalanche and transit-time. The resultant new type of transistors is called CATT (Controlled Avalanche Transit-Time Triode) [19]. So far this type has not found any larger application.

We shall now discuss progress in the areas of diode generators and amplifiers. The oldest known and widely used cascade-transit diode continues to be an important element of microwave systems, and the only one which can provide a large power and high efficiency above 12 GHz (Fig. 12). Gallium arsenide diodes for

Fig. 13. Amplifier of continuous power 5 W at 35 GHz with cascade-transit diodes.
1 - 4 diodes; 2 - 8 diodes



continuous work and impulse silicone diodes give efficiencies up to 35% in the X-band. At higher frequencies reaching 100 GHz, one can obtain power exceeding one watt, when using a double zone of wear and a diamond base [20].

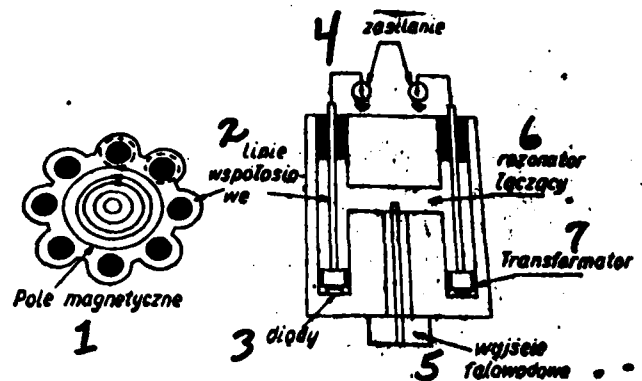
The diodes discussed can work in a broad range of frequency from 3 to 300 GHz. The lower limit mentioned here is reached by new types, which employ the metal-semiconductor junction formed by means of implantation of ions. As a result, one obtains continuous power of over 10 W, at an efficiency of about 20% [21, 22].

Technical literature contains descriptions of a number of construction designs for amplifiers of power up to 10 W with cascade-transit diodes of gallium arsenide and silicon at centimeter waves [23, 24]. However, the latest achievement is a 35 GHz amplifier with amplification 33 dB and the width of one-decibel band larger than 700 MHz, constructed from diodes of gallium arsenide (Fig. 13). The output power of 5 W is obtained due to the interconnection of 8 diodes in the resonator by means of magnetic fields of the coaxial resonators (Fig. 14) [25].

In the impulse work of a cascade-transit diode, one can apply its special kind called TRAPATT, which utilizes oscillations of the electron-hole plasma which is formed by rebounding of the cascade wave running through diode from the wideband circuit [12]. The impulse powers of the order of 10 W are created in the generator on band X at the efficiency higher than 2%, although the main range of work lies at lower frequencies up to 400 MHz. The record achievements here include obtaining peak power up to 120 W at 44% efficiency,

Fig. 14. Resonance interconnector of 8 generators with cascade diodes.

1 - magnetic field; 2 - coaxial lines; 3 - diodes; 4 - supply; 5 - waveguide outlet; 6 - connecting resonator; 7 - transformer.

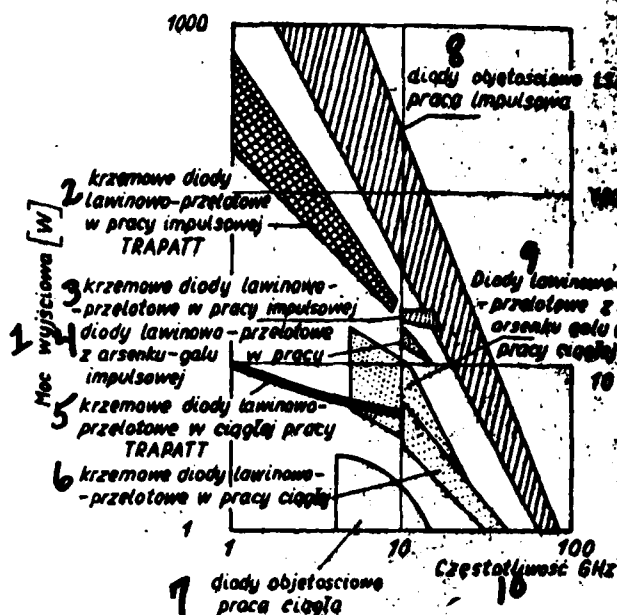


at 2.3 GHz for 0.5 microsecond impulses of the one percent utilization of the period [21]. Diodes working in the described mode can be connected in series, providing the power exceeding kilowatt at about 2 GHz. The placement of several diodes connected in series on one diamond cooler makes it possible to obtain semiconductor instruments with power of several tens of watts [26]. The work of diodes in TRAPATT mode can be improved by means of the optical release of charges, e.g., by means of a semiconductor laser [27]. However, of greatest interest are TRAPATT amplifiers because of the possibility of their use in phased antennas. At the frequency of about 3 GHz, one can obtain up to 100 W of peak power, at 30% efficiency and amplification 6 dB. The three-decibel width of band exceeds somewhat 15% [28].

The diodes of transit-time include the BARRITT diodes, in which the charge is introduced through the p-n junctions. These diodes are less noisy than the cascade diodes, hence they are favorites for application in local oscillators [20, 29]. The fact that they generate less power does not limit their application. They are manufactured by some companies, but they are not widely known. On the other hand, diodes operating on another principle, namely by creating oscillations in the volume of a semiconductor, find broader applications. This semiconductor is usually gallium arsenide, or lately more and more frequently indium phosphide. We know them most often under the name of the Gunn diodes, although this name is connected only with the basic mode of work. As is seen from Fig. 12,

Fig. 15. Comparison of power achievable by different types of diode generators.

1 - output power (W);
 2 - cascade-transit diodes of silicon in impulse work TRAPATT; 3 - cascade-transit diodes of silicon in impulse work; 4 - cascade-transit diodes of gallium arsenide in impulse work; 5 - cascade-transit diodes of silicon in continuous work TRAPATT; 6 - cascade-transit diodes of silicon in continuous work; 7 - capacity diodes in continuous work; 8 - capacity diodes LSA in impulse work; 9 - cascade-transit diodes of gallium arsenide in continuous work; 10 - frequency GHz



the Gunn diodes do not reach so far in the frequency band as the cascade-transit diodes, but they are less noisy than the latter by about one order of magnitude. The record generating data for diodes of gallium arsenide are 70 mW at 60 GHz, but only at the efficiency of 2% [30].

The Gunn effect was discovered on a semiconductor material other than gallium arsenide, namely, indium phosphide; but for a long time, gallium arsenide reigned in the discussed application as a better known material. Lately, it has been found that indium phosphide can give better efficiencies and less noise, particularly on transition to millimeter waves [31]. The continuous work at high efficiency is limited, however, to 10 milliwatts or so; but in the impulse work, one can obtain the level of work of 5 - 10 W at 15% efficiency in this range of frequency [12]. The generator effects in indium phosphide are observed even at 80 GHz [31]. At present, intensive work is being done on this material and on diodes made of it, and one can expect that such diodes will soon be introduced generally into company catalogs.

The Gunn diodes find broad application in power amplifiers; diodes of gallium arsenide supply, for instance, 100 mW at 1 dB compression -- the magnification then is 28 dB at 14 GHz [30]. On the other

hand, diodes of indium

phosphides can be used suc-

cessfully at higher frequencies (e.g., 26-40 GHz) with noise 11 - 14 dB. The corresponding diodes of gallium arsenide have noise up to 23 dB [31, 32]. Amplifiers of the described types compete successfully with amplifiers having field effect transistors. Comparison of the power obtainable with different types of diode generators -- continuous and impulse mode -- is given in Fig. 15. The highest values of power are expected from the Gunn diodes working in the LSA (Limited Space Accumulation) mode; however, so far this is only wishful thinking based on limited results of laboratory work.

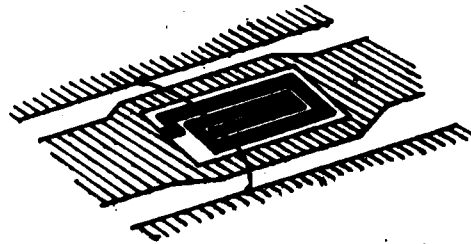


Fig. 16. Induction element co-working with microline.

The progress in semiconductor microwave instruments is inseparably connected with introduction of new types of packaging. Usually, producers of microwave instruments use existing frames also suitable for other purposes. However, high quality instruments dictates the application of special types of frames, particularly when they have to contain matching systems [33]. Introduction of new insulating materials into the frame construction, such as beryllium oxide or quartz, should improve the properties of microwave instruments considerably.

At present, passive microwave instruments do not enjoy an intensive development, but progress in this area is also seen in the range of semiconductor devices. Here one can see possibilities of the utilization of the echo of spin waves in yttrium granates to form delay lines on microwaves. Circulators and ferrite insulators

have become the common equipment items in microwave apparatuses, and also filters containing ball resonators of yttrium granate are used [14].

The condensed (grouped) elements, e.g., for band B, about which we spoke at previous conferences, begin to return and appear in both the generators and filters (Fig. 16) [34, 35]. One can note progress also in the work on microlines, particularly on the millimeter waves [18].

A considerable majority of microwave systems mentioned here are produced by hybrid technology, which is particularly suitable for low-quantity production [36]. Its application is justified by the reduction of production defects, and reduction of the time of control, hence lowering of the costs. A great need for this type of production will become apparent on the market of satellite television receivers. The present work goes mainly in the direction of integration of field effect transistors in systems of microwave amplifiers, mixers and amplifiers at intermediate frequency [18, 38].

Further progress of monolithic microwave technology is connected with an increase of the speed of work of logical systems [39], and particularly with transition from silicon to gallium arsenide as their basic material. Initially, the Gunn effect was utilized for a fast change of states of the system, achieving delays 60 ps. Then, use was made of the excellent transfer properties of the field effect transistors of gallium arsenide [41] from direct current to 4 GHz, with possibilities of work above 5 GHz [39, 40]. A low consumption of power by logical elements of this type makes possible the designing of complex systems, whose work is limited by thermal losses of power. The monolithic integration is the only practical solution for sub-nanosecond logic systems.

At the end of this survey of scientific and technological progress in the field of solid state microwave electronics, one should also call attention to the development of sub-millimeter

waves and light waves technology. Although these problems are outside of the main topic of the conference, it is worth keeping in mind that their progress is connected with utilization of methods developed by microwave technology.

A similar type of connection exists also between proceedings of the conference and the technology of mechanical waves in the elements of solid state used in microwave instruments (microwave acoustics) [42, 43].

Concluding this article, it is necessary to mention the forecast for the five-year period 1976 - 1980 on the world market: It is anticipated that the number of semiconductor instruments will increase by 40%, and the number of passive subsystems and cables with junctions -- by 50% [44]. Our national economy, naturally, will demand a higher growth dynamics.

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